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Flight System Autonomy Needs for Planetary Exploration Missions

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ABSTRACT

There is a general realization within NASA that "onboard autonomy" is needed. Exact specifications of what that means are often vague at the onset of the mission design process. Moreover, autonomy technology is generally not well understood by the spacecraft design community, which complicates matters considerably. The work described in this paper is an effort to better define the autonomy needs for future planetary exploration missions based on the current mission designs for a set of solar system exploration missions. This is part of an ongoing NASA exercise to define technology needs requirements in order to better set technology funding priorities. Autonomy technology needs requirements are classified as either algorithms or architectures. The algorithms have heritage in AI research domains, such as planning and scheduling, monitoring & diagnosis, executives, and image processing. Architectures represent software systems for carrying-out mission objectives, such as low-cost routine operations, landing and hazard avoidance, and opportunistic science data collection.

1.0 INTRODUCTION

The NASA trend towards "smaller, faster, better, cheaper" spacecraft that began several years ago has resulted in a cultural and technological shift that favors more aggressive use of software technology onboard the space platform. There are three basic reasons for this. One is to migrate mission operations functions traditionally performed on the ground to the spacecraft to lower mission operations cost. The second justification is to provide capabilities onboard that are necessary in order to contend with the round-trip light delays. A third justification is to decrease the amount of communication (frequency of contact and data volume) to decrease the loading on NASA's over-constrained Deep Space Network antennas. Typically, new software technology is classified as mission "enabling" or "enhancing." Performing joystick control, for example, is not possible when light-time delays are significant. The solution, therefore, is to provide "mission enabling" software technology to close control loops onboard in order to achieve the most basic mission objectives. Enhancing technology tends to be software for lowering total mission cost, DSN loading, or providing more enriching science data return. Enhancing technology enters the mission design process as a candidate solution but may be ruled-out as mission design trade-studies occur. Enabling technology, on the other hand, is likely essential for mission success.

Another way to think of autonomy as it relates to space missions is that the term represents the current body of information technology (IT) research as applied to space missions and that there will be, in fact, a continuum of software solutions for future missions. One could also argue that NASA missions, especially the unmanned ones, have long been autonomous. Providing capabilities onboard to enable the spacecraft to move to a "safe-hold" state or to switch to a back-up unit in the event of a failure are examples of behavior that one could define as being autonomous. Onboard autonomy today, however, suggests more comprehensive capabilities that can replace major mission operations functions, suggest new paradigms for mission operations, and enable new classes of missions.

2.0 PLANETARY MISSION SCIENCE GOALS AND STRATEGIC MISSIONS

The exploration of the solar system is driven by the desire to understand the planets and the environment in which they exist. The current set of strategic missions consists of the eight highest priority science investigations in the field of planetary exploration. These missions have ambitious scientific goals and as a result, push the limits of technology capability. The following paragraphs describe the current concept for each mission.

COMET NUCLEUS SAMPLE RETURN

The Comet Nucleus Sample Return (CNSR) mission will encounter and land on a comet, collect and store a sample of the comet material, and return it to Earth for study. The mission has several key technical challenges requiring autonomous operations; a long cruise period which requires adaptive sequencing and fault monitoring and recovery; complex operations near the comet and on the surface requiring autonomous decision making and hazard avoidance; and science operations in a relatively unknown environment. Each of these elements requires the spacecraft to operate essentially independent of the ground controllers for some period of the operation and local decision making enables the mission to deal with unanticipated conditions and collect high priority science data.

EUROPA LANDER

Europa is one of the most scientifically interesting objects in the Solar System because of the strong possibility that a liquid water ocean exists underneath its ice-covered surface. If a subsurface ocean exists on Europa, it can be assumed to contain both organic molecules and heat sources from tidal effects, the decay of radioactive elements, and geophysical mechanisms. Europa's subsurface ocean environment may be similar to that of the deep ocean hydrothermal vents on Earth where remarkable life forms have been detected. The possibility of finding traces of biotic or pre-biotic materials has led to a high science interest in a Europa Lander mission.

This mission is technologically challenging in several areas and requires autonomous capability to complete essential elements of the mission. Most critical is the entry, descent and landing phase, which must be accomplished under local control. In addition, the long cruise period requires onboard health maintenance and fault monitoring to insure the successful completion of the mission.

EUROPA ORBITER

Prior to the Europa Lander mission, NASA plans to send an orbiter to assist in determining presence of Europa subsurface water, measure ice thickness and interior properties, and image surface features. This mission will add to the collection of scientific data gathered by the Galileo mission, which currently is conducting periodic flybys of the Jovian moon. Autonomy technology needs requirements for this mission are presented as an example in Section 4.

NEPTUNE ORBITER

The Neptune orbiter mission is a continuation of the detailed exploration of the outer planets in the same manner as the Galileo mission to Jupiter and the Cassini mission to Saturn. The overall science goals of the Neptune Orbiter Mission are; to study the rings, ring arcs, and shepherd satellites; map Triton's surface features and examine its geologic history; examine the composition, structure and dynamics of Neptune's atmosphere; and image and determine the densities of the satellites Larissa, Proteus and Nereid. To accomplish these activities at the great distances requires autonomous health maintenance for the long cruise and orbital operations.

PLUTO-KUIPER EXPRESS

Pluto is the only planet in the solar system that has not yet been explored. A flyby of the Pluto-Charon system is planned along with a continuing mission to one or more of the asteroid-sized Kuiper objects. The major objectives are to characterize surface geology and morphology of Pluto and Charon, map the surface composition of Pluto and Charon, and characterize the neutral atmosphere of Pluto and its escape rate.

TITAN ORGANICS EXPLORER

The Titan Organics Explorer mission is a follow on to the Cassini/Huygens Probe, and provides a detailed in-situ exploration of the Saturnian moon Titan. To meet the objectives, several mission concepts have been studied, including both aerobot and rover missions. Autonomous operations for the critical atmospheric entry and descent phases is required, as well as automonous operations for the surface and atmospheric vehicles.

SATURN RING OBSERVER

The Saturn Ring Observer (SRO) mission is designed to place an observing spacecraft in an unique orbit around Saturn to observe the rings. This unique orbit places the spacecraft above the rings in synchronous rotation with the ring particles, and the spacecraft observes the interaction and dynamics of the particles. The overarching goal is to understand ring processes and evolution as a model for the origin of planetary systems. This will involve measurement of ring particle physical properties, dynamics & spatial distribution. To do this, a non-Keplerian orbit has been developed which requires periodic orbit maintenance activities to maintain its position relative to the rings. This operation must be controlled locally in response to the dynamic environmental conditions.

VENUS SURFACE SAMPLE RETURN

The Venus Surface Sample Return (VSSR) mission is a very challenging mission. The principal science objective is to return samples of atmospheric and surface material to Earth for detailed chemical analysis. Knowledge of the surface chemistry of Venus is based on limited observations done by the Venera landers. Understanding the surface material will help in calibrating models of the evolution of the atmosphere and the interior. In the same manner as other sample return missions, autonomous capabilities are required for atmospheric entry, descent and landing, and for surface operations. Venus places an additional constraint on the surface operations due to the extremely hot environment (~760 K at the surface). The total surface operation is limited to approximately 1.5 hours, and must include automomous decision making ability to meet the science goals.

3.0 MISSION CAPABILITY NEEDS

An intermediate step in identifying autonomy technology for a given mission or across the entire set of missions is to understand the features of the mission and how the mission may stand to benefit if more substantial software technology is deployed. Figure 3.1 summarizes these mission characteristics for six of the eight candidate missions. From this, it is possible to begin understanding what autonomy functions are required and candidate technology solutions. The first line in Figure 3.1, "Long Cruise Period," is often sited as a justification to implement flight software capabilities that reduce the need for ground contact. Dynamic landing environments, such as on a comet may suggest closing the control loop onboard in order to land with acceptable risk. Only detailed trade-studies involving many mission design variables can yield the final software design solution for a given mission. In the end, if significant onboard processing is required, it is likely because the detailed trade studies have determined that enhanced onboard software can deliver the solution that best meshes with cost, risk, and schedule constraints.

Figure 3.1
Summary of Mission Autonomy Drivers

Long Cruise Period	7-8 Years	9 Years	6.5 Years **+2 yrs for OI**	6 Years	2-3 Years	10 Years
Dynamic Landing Environment	Yes	N/A	Yes	Yes	Yes	N/A
Highly Adaptive Surface Operations	Yes	N/A	Yes	Yes Aerobot Control	Yes	N/A
Long Encounter Period	No	No (30 days)	No (10 days)	No (30 days)	No	Yes (2-3 Years)
Entry, Descent and Landing Reporting	Yes	No	Yes	Yes	Yes	No
Autonomous Science Operations	Yes	No	Yes	Enabling for Aerobot, **Enhancing for Rover**	Yes	No

- Driving requirement for autonomy
- Good justification for autonomy
- Autonomy not required or N/A

Another part of the NASA activity is to roll-up the technology needs across the entire mission set. It may be the case that one mission has the need that will drive autonomy performance requirements in that area. Or perhaps several missions can benefit in much the same manner by having a certain software capability. Regardless, the mission capability needs at the roll-up level fall into two basic categories. One is the need to migrate ground functions to the spacecraft to lower mission operations cost and/or enhance the mission in some way (such as improving data quality). The other basic need is to work contend with round-trip light delays associated with planetary exploration missions in order to achieve essential mission requirements. The third reason why autonomy may be valuable to NASA involves utilization of the oversubscribed Deep Space Network (DSN) antennas. This is ultimately a cost issue (the DSN could always build more antennas), but it also involves providing capabilities to enable most effective use of this scarce resource. While a valid concern, DSN loading is usually left out of individual mission design processes because agency-wide infrastructure planning and utilization issues are much higher-level concerns.

4.0 REQUIRED AUTONOMY TECHNOLOGIES

In actuality, an autonomous system in the space mission context consists of both hardware and software. For purposes of this discussion, we limit autonomy to be software only but realize that hardware provides many underlying enabling capabilities. Also implicit here is that at the mission design level, the appropriate trade-offs have been made to determine the autonomy need. For the purposes of developing software needs requirements, it is most convenient to divide software into algorithms and architectures. The algorithms map well to research thrusts within the artificial intelligence community. Autonomy architectures map well into mission needs and consist of combinations of autonomy algorithms (and other algorithms) as appropriate for a given mission design and desired functionality. In defining technology needs, it is imperative to specify requirements at both the algorithm and the architecture level. The requirements breakdown structure shown in Figure 4.1 was created to classify the relevant autonomy technology needs.

Figure 4.1
Autonomy Breakdown Structure

Algorithms	Automated planning & scheduling Intelligent control Instrument data processing Monitoring & diagnosis

	Navigation algorithms
System software	Software systems for low-cost operations Safe landing systems Software systems for in-situ hazard avoidance (not used for these six missions) Entry, Descent, and Landing (EDL) problem reporting system software Autonomous Sample Selection Intelligent Sensors Autonomous rendezvous and docking Autonomous navigation

Autonomy algorithms typically represent ground functions that are migrated to the spacecraft. The functional disciplines, and research thrusts, are planning & scheduling, smart executives, onboard science, onboard guidance, navigation, and control, and intelligent fault management, and autonomous navigation. AI research programs currently exist within NASA in each of these areas.

Spacecraft are typically commanded through intricate, pre-planned sequences. Generating these sequences is an expensive, human-intensive endeavor. Current research activities are laying the foundation for performing commanding at a much higher, goal-oriented level. In order to do this, the onboard software must be able to plan the exact sequence of events based on its own observation of the environment, resource constraints, and the stated priorities of the mission. If this is done, the spacecraft is less costly to operate because the need to carefully construct highly detailed sequences on the ground has been drastically reduced. The potential for increased science return is also achieved because the spacecraft can react autonomously to unanticipated science opportunities and can better optimize use of spacecraft resources.

Smart executives replace traditional sequencing engines with a more closed-loop software engine capable of resolving higher level goals into executable commands. In order to do this, the smart executive must be able to react to unexpected events, dynamic environments, and errors or inconsistencies in the commands that have been generated. The executive acts as the overall coordinator of spacecraft activities and manager of spacecraft resources.

Monitoring & diagnosis technology provides yet another requisite piece for closing the control loop onboard the spacecraft. There are aspects of automated monitoring that relate to both the nominal and anomalous system behavior. For the anomalous case, NASA has traditionally viewed monitoring in terms of fault detection, isolation, and recovery. This approach gives rise to threshold-based anomaly detection systems. If there is a problem, an alarm limit typically moves out of nominal limits and a fault response algorithm is initiated to attempt recovery or place the spacecraft in a safe-hold condition. Next generation monitoring extends fault protection capabilities but also emphasizes monitoring of nominal conditions for the purposes of generating reports to assure ground personnel that the mission is proceeding as planned. Examples of new capabilities in autonomous monitoring are neural networks, adaptive alarm limits, model-based reasoning, onboard empirical and/or model-based summarization, and onboard data archiving.

Onboard instrument data processing encompasses a wide range of algorithms designed to either enable the spacecraft to be more survivable or to increase the science data return to earth. Techniques that leverage instrument data tend to involve use of data mining technologies, such as pattern recognition, machine learning, and knowledge discovery. Also applicable are methods that provide for more adaptive and event-driven science data compression. Onboard image processing algorithms can autonomously identify features of known interest, edit the science data to contain only the important features, and prioritize science data for downlink to Earth. This class of algorithms also enables the space system to be capable of reacting to unexpected science events and can signal the spacecraft to perform follow-up observations without ground contact. Data mining technologies can also be used to identify hazards, either for rovers or during descent and landing operations. .

The term autonomy architecture, for purposes of this exercise, implies the creation of a system-level software product in order to achieve certain mission objectives. Although each autonomy algorithm provides a necessary function, it is likely for a given deployment that many algorithms would work together to carry out mission objectives. For example, an onboard science algorithm may detect an event and would signal for a follow-up observation. The onboard planning and execution environment would receive that goal and resolve it based on mission priorities and constraints at that time. Another reason why making the distinction between architectures and algorithms is important has to do with the various implementation options available for incorporating the autonomy components. The boundary between onboard executives and planners, for instance, can be quite fuzzy. This is because both disciplines involve resource management, command generation, and other shared functionality.

Since the component autonomy algorithms have heritage in AI research disciplines, understanding the relevance of each of these disciplines to the higher-level architectures is important. That leads to the third reason to call-out architectures as requirements, which is that architectures show mission relevance. The final deployed software system for a space mission may actually combine the "architectures" as identified in the requirements breakdown structure. For example, a mission system architecture may support both "low cost operations" and "adaptive science." This form of overlap, for the purposes of this NASA exercise, is largely irrelevant. Using the breakdown structure to tie autonomy algorithms and research disciplines to mission system software needs is the more important distinction to make in the current NASA planning exercise. The result is an autonomy requirements breakdown structure that is useful to both the mission design community and the technology development community.

There is also a third category of autonomy, which is ground-only software. The ground software can then be divided into either design-time or mission operations software. Examples of design-time autonomy could include autonomous design environments or mission simulations that are substantially more complex than the current state-of-the-art. For mission operations, planning & scheduling technology can be used to assist ground operators or to automate the deep space network scheduling operations. Ground autonomy, although completely valid, has not been included in the current SSE planning activities for now.

Figure 4.2 summarizes the autonomy technology needs for the Europa Orbiter mission. Mission attributes are the features of the mission that provide justification for considering autonomy software. Capability Requirements are the specific performance objectives for the autonomous system.

Figure 4.2
Europa Orbiter Autonomy Needs Example

Autonomy Element	Mission Attributes	Capability Requirements
Automated planning & scheduling	Light delays along the trajectory, opportunistic science during Jupiter flyby, extended mission amenable to increasing levels of autonomy	Enhancing technology if planning & scheduling technology is sufficiently mature. Requirement is to leverage the technology if possible to increase science return during cruise flyby and extended mission.
Intelligent control	Long cruise period requiring minimal ground contact except when unexpected problems occur that are not resolvable by onboard software.	Time-windowed, prioritized macro execution, greater degree of closed-loop control and less ground modeling and prediction than in current mission operations, undersubscribed high-priority macros, oversubscribed low priority macros, onboard sequence recovery after fault conditions
Onboard instrument data processing	Limited bandwidth due to mission distance from earth	Perform progressive resolution or other forms of data compression during encounter operations to maximize science data return
Monitoring & Diagnosis	Long cruise period, long round-trip light delays	Continuous monitoring during cruise to determine the urgency of ground contact. Adaptive onboard engineering data summarization that enables all relevant telemetry to be downlinked in a single telemetry pass after it has been determined by flight software that a pass is required. Adaptive onboard engineering data archive, onboard trending and automated fault detection and isolation. Two week safe-hold capability.
Software system for low-cost operations	Long cruise period, long round-trip light delays, limited communications bandwidth	Unified flight-ground architecture for low-cost software migration supports deferred software development throughout long cruise period, enables spacecraft-initiated (Beacon) operations with adaptive monitoring

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